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A standard device to measure flows accurately and precisely was required by the U.S. Environmental Protection Agency (EPA) to establish an air pollution field auditing system capable of generating pollutant concentrations in the parts per million and parts per billion range. The establishment of a standard normally requires the device possess accuracy and precision specifications at least an order of magnitude (one decade) better than the devices to be calibrated. In the measurement of low flows (less than 20 liters per minute) there are many devices capable of 1-2 percent accuracies. This figure generally represents a percentage of full scale. When properly calibrated, the laminar flow element (LFE) is capable of obtaining accuracies better than .3 percent of reading.

The LFE's characteristics, calibrations, limitations, and usage in EPA's National Performance Audit Program are presented.

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INTRODUCTION

The Atmospheric Research and Exposure Assessment Laboratory (AREAL) of the U.S. Environmental Protection Agency (EPA) at Research Triangle Park, NC has been conducting performance audits of ambient air pollution monitoring analyzers for a number of years. To obtain audit results of known quality, a standard device to measure flows accurately and precisely was required to establish an air pollution field auditing system capable, by dilution, of generating pollutant concentrations in the parts per billion range. The establishment of a standard usually requires that the device possess accuracy and precision specifications at least an order of magnitude better than the devices to be calibrated. In the measurement of low flows, less than 20 L/min, many devices are capable of 1-2% accuracy. When properly calibrated, the laminar flow element (LFE) is capable of obtaining accuracies better than 0.5%. Although this figure is not a decade below the specifications of other devices, it does represent a $\pm$0.5 % of reading, whereas the other devices generally specify $\pm$1-2% of full scale.

For this reason, and because the LFE exhibits such a linear and repeatable response curve, it was chosen as the laboratory standard. The laboratory presently has 6 LFEs calibrated by the National Institute of Standards and Technology (NIST), (formerly National Bureau of Standards); and used only once each year to verify the calibrations of the other 30-40 LFEs used by other EPA personnel. With the exception of one element in the 2-20-cm^3/min range, the LFEs exhibit an overall uncertainty of less than $\pm$0.5%, of which 0.1% is systematic error. The 2-20-cm^3/min LFE was quoted by NIST as having an overall uncertainty of $\pm$1%.

The material presented here explains (1), the conditions under which the LFE can best be utilized to accurately measure the flow of clean, dry air and (2) the computer program used to maintain the accuracy and precision of the original calibration of the LFE.

Initially, laminar flow elements were used to measure flows through the flow restrictors of a dilution system. Since that time EPA has used them to calibrate and certify all types of flow measuring and controlling systems for state and local air monitoring programs throughout the United States.

MATERIALS AND METHODS

A laminar flow element is a device whose output is a pressure differential which is directly related to the volume rate of flow passed through it. The LFE produces a linear pressure response in the 15-210-mmH_2O range for flow rates which extend over a one decade range. Thus, the range of flows from 10 cm^3/min to 100,000 cm^3/min could be measured by utilizing only four LFEs.

In the process of making accurate measurements of physical phenomena it is always necessary that the measuring device be well characterized and understood. Three factors affect the response curve of the LFE, viscosity, compressibility and gas density. The viscosity and density are temperature dependent. The density, compressibility and, to a lesser extent, the viscosity, are pressure dependent. Thus, the gas temperature and pressure must be accurately known and referenced to a common point. Since the element's response is a pressure differential, it too must be referenced to this common point.

Even though the LFE inlet was chosen, in practice, the inlet, outlet or a midpoint halfway between the two pressure taps could have been used as the reference. AREAL's standard LFEs have been calibrated by referencing the flows, the pressure differentials across the devices, the temperatures, and the absolute pressures to the inlet. A NIST calibration consists of 50 data points, 5 flows measured 10 times for each LFE. The data is given in English units. With the calibration data, a curve in the form of $Y = a + bX + cX^2$ (flow equation) is derived for each element, where $Y = P/uQ$ (flow coefficient) and $X = rP/u^2$ (viscosity coefficient). The a, b, and c constants are obtained by a parabolic regression of the 50 calibration data points where:

r is the air density in lb_m/ft^3
P is the pressure differential across the LFE in lb_f/in^2
u is the air viscosity in lb_m/ft-sec
Q is the flow rate in ft^3/min

Once the calibration curve is obtained, the a, b, and c constants are stored as data for that particular LFE in a computer program (1) developed by the author. To determine flows utilizing that particular LFE, the temperature, barometric pressure, and pressure drop across the LFE must be measured to obtain r, P, and u. Once these factors are known and utilized with the calibration constants stored in the program, flows can be calculated rapidly.

A computer program was developed to take into account the LFE's calibration constants, English-to-metric conversion factors, and the various factors governing the measuring instruments' characteristics. To measure the output of the LFE requires a differential manometer. Initially a water manometer was chosen because of its accuracy and precision (0.001 mmH_2O). However, to make an accurate measurement of the absolute pressure at the inlet of the LFE, corrections must be made for various manometer and barometer characteristics. The inlet pressure is obtained by measuring the barometric pressure with a mercury barometer and then adding or subtracting the pressure differential across the LFE, depending on whether the air is being pushed or pulled through the LFE. The equation for the absolute inlet pressure is

$$P_{abs} = P_{atm} \pm P(1 - P_{air}/P_{water})g_1/g_o \qquad [1]$$

where: P_{abs} = absolute inlet pressure
P_{atm} = barometric pressure corrected to 0^oC
P = (manometer height reading) x (manometer fluid density - density of medium above fluid)
P_{air} = density of air
P_{water} = density of water
g_1 = local acceleration of gravity
g_o = calibration reference acceleration of gravity (NIST)

Each of the above factors is addressed in the following text.

To maintain precision and accuracy of the barometric readings, the temperature of the barometer is obtained and all measurements are corrected to 0^oC. To make this correction, a table found in the literature (2) was approximated with a series of equations.

The correction factor (C.F.) turned out to be a linear function of mercury density with temperature (C.F.= A + BT, where A and B are pressure dependent and T is the temperature in degrees centigrade). The C.F. is applicable for barometric pressures between 730 and 770 mmHg, the pressures generally encountered in this laboratory. The correction factor must now be subtracted from the barometer's reading.

To determine the manometer corrections, the fluid is assumed to be water and the medium above the water, air. Thus, the equations for the density of water and air are utilized. The expression for the density of water (3) is

$$P_{water} = [999.84 + (0.067983)*T - (0.009106)*T^2 + (0.000101)*T^3 - (0.0000011)*T^4]*10^{-3}.$$

The expression for the air density is

$$P_{air} = K(P_{atm}/ZT)$$

where: K = conversion constant for English to metric units;
P_{atm} = corrected barometric pressure [barometer reading (mmHg) - correction factor];
Z = air compressibility function; and
T = temperature (^oC).

The air compressibility factor (3) is $Z = 1 + B/V + C/V^2 + D/V^3$ and contains three terms (B, C, D) dependent on the temperature in Kelvin units and a fourth (V) dependent on the temperature and the corrected barometric pressure.

The gravitational terms from [1], g_l and g_o, are dimensional constants and are 32.146 $ft\text{-}lb_m/lb_f\text{-}sec^2$ for Raleigh, NC, and 32.174 $ft\text{-}lb_m/lb_f\text{-}sec^2$ for NIST at Gaithersburg, MD.

The absolute pressure of the LFE inlet is now defined. Using equation [1] to determine the absolute pressure assumes that one of the ends of the LFE is always open to atmospheric pressure. If the air is being pushed through the LFE the second term in the pressure equation is positive. If the air is being pulled through the LFE, the second term is negative. Care must be exercised if the inlet is left open to the atmosphere. A risk of contaminating the LFE with ambient particulate matter exists unless a low pressure drop filter is used. If a filter is used, the pressure drop across it must also be taken into account in the pressure equation.

The calibrations are performed by using clean dry air. High levels (greater than 80% relative humidity) of moisture can also affect the calibration curves.

The viscosity equation(3,5)

$$u = [12.185 + 0.03205(T_o - 293.16) + 0.01705(P_o-1)]*10^{-6}$$

is pressure and temperature dependent. The pressure (P_o) is expressed in atmospheres and the temperature (T_o) in Kelvin units. Now the viscosity coefficient (X) can be calculated and substituted into the calibration curve

$$Y = a + bX + cX^2,$$

the Y term is equivalent to the flow coefficient, and the flow can be solved for Q = P/uY. Thus, the total expression for the flow becomes

$$Q = P/u[a + brP/u^2 + c(rP/u^2)^2].$$

In 1980 the computer program was checked by NIST personnel by giving them a series of values of differential pressure, temperature, and barometric pressure for an LFE which they had previously calibrated. NIST ran the values through their program for EPA's LFE, and they were checked against EPA's program. All of the values were within 0.03%. Care must be exercised when using the above corrections, because they assume a water manometer and a mercury-filled barometer. If other types of sensors are used, their characteristics may have to be accounted for in the program. Similar cautions apply if a gas other than air is used. For instance, the density and viscosity terms will need to be changed if pure nitrogen is used as the gas flowing through the LFE. Pure nitrogen produces a 3-4% error if these terms are not accounted for.

RESULTS AND DISCUSSION

The resulting computer program, combined with the newer electronic differential manometers and digital thermometers, has given the laboratory personnel a new, fast, and accurate method of measuring flows.

The electronic manometers with the capability of detecting minute changes in pressures (0.01mm H_2O) have enabled us to see the cycling effect of mass flow controllers coming to their equilibrium point. Calibration of orifices, mass flow meters and controllers, dry gas meters, and other flow measuring or controlling devices has been made much easier. The time required for each has been drastically reduced. A 10 point calibration of a mass flow controller, complete with a graphic printout comparing the standard LFE flow with the output reading of the flow controller, can now be done within 30 minutes.

Using a properly sized LFE can also reduce the error made when making a measurement of a flow stream. The flow stream restriction and thus, the error can be reduced by choosing an LFE having a small pressure drop across it for the flow that is being measured.

Two cross-checks were performed on different LFEs during the early years of the program. NIST calibrated a type 12 LFE in July 1978. In July 1980 a type 11 LFE was calibrated at NIST. In December 1980 the two were compared. The difference in slope was 0.74%. In October 1983 a similar analysis was conducted with two LFEs calibrated by NIST in July 1979 and again in June 1983. Ten flows calculated with the 1979 calibration curve, were compared to ten flows calculated with the 1983 calibration curve; the following regressions resulted.

$$Y = A + BX$$

where Y = 1979 flow; X = 1983 flow; A = y axis intercept; and B = slope or ratio between flows. For the one LFE in the 75-750-cm^3/min range, $Y = 0.3318 + 0.9933X$; for the other LFE in the 1100-11000-cm^3/min range, $Y = -14.0645 + 0.9983X$. Both cases show the excellent repeatability capabilities of the laminar flow elements over a period of four years, 0.67 and 0.17% respectively.

By cycling a group of LFEs through NIST each year, AREAL maintained accuracies of $\pm$ 0.5% for the entire set of flow standards. Recently the laboratory has been able to afford a complete set of LFEs calibrated by NIST. This allows a set of standards to be used only once a year to certify the other 30-40 LFEs used by AREAL.

Today many of the laminar flow elements are used in the National Performance Audit Program to audit the flows of dichotomous samplers across the United States. The LFEs are mailed out to participants with an electronic differential manometer, an electronic barometer, and an RTD temperature sensor to determine flows of the audited device. The station operator at the site records the readings from the three sensors on an accompanying data form. These figures are then entered into the LFE computer program, and the audit flow is computed. Results are then mailed back to the monitoring program.

The laminar flow element has proven to be a very useful device for flow measurements. Certain precautions are needed when utilizing them, but they can provide accurate, precise results for many years of service.

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Key Words

Page 1: Laminar flow element, accuracy, precision, dilution system
Page 2: Viscosity, density, pressure differential
Page 3: Manometer, gravity
Page 4: Filter, particulate matter
Page 5: Calibration, electronic differential manometer
Page 6: Standards, dichotomous samplers